

Synopsis of a Unified Theory for All Forces and Matter

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(Dated: November 9, 2016)

Assuming the $(9 + 1)$ -dimensional Kaluza-Klein gravity interacting with elementary matter fermions, we propose an informationally-complete unified theory for all forces. Due to entanglement-driven symmetry breaking, the $SO(9, 1)$ symmetry of the $(9 + 1)$ -dimensional spacetime is reduced to $SO(3, 1) \times SO(6)$, where $SO(3, 1)$ [$SO(6)$] is associated with $(3 + 1)$ -dimensional gravity (gauge fields of matter fermions). The informational completeness demands that matter fermions must appear in three families, each having 15 independent matter fermions. After quantum compactification of six extra dimensions, a trinity—the quantized $(3 + 1)$ -dimensional gravity, the three-family fermions of total number 45, and their $SO(6)$ gauge fields—naturally arises in an effective theory for the $(3 + 1)$ -dimensional spacetime. Both the fermion family state space and the compactified space are a simple three-state system equipped with an ungauging, e.g., $SO(3)$ structure. Possible routes of our theory to the Standard Model are briefly discussed.

PACS numbers: 04.50.+h, 12.10.-g, 04.60.Pp

The tendency of unifying originally distinct physical subjects or phenomena has profoundly advanced modern physics. Newton’s law of universal gravitation, Maxwell’s theory of electromagnetism, and Einstein’s relativity theory are among the most outstanding examples for such a unification. The tremendous successes of modern quantum field theory, i.e., the Standard Model (SM), motivate the ambition of unifying all the four forces known so far—a kind of “theory of everything”. The superstring theory and quantum gravity (particularly, loop quantum gravity—LQG [1–4]), both with remarkable results, are two tentative proposals. Here we take a more “orthodox” viewpoint following the SM and LQG, rather than the superstring theory.

The tradition of physics, initiated from Newton, is to describe a physical system by dynamical laws, usually in terms of differential equations. To determine the (classical or quantum) state of the system, the initial (as well as boundary) conditions have to be given regardless of dynamical laws. Different allowed initial conditions lead to different solutions to dynamical laws. Such a tradition is called Newton’s paradigm [5], which is believed not to apply to the whole Universe. For the unique Universe the initial conditions must themselves be a part of physical laws. Thus, if any form of the theory of everything is conceivable at all, it must unify dynamical laws and states, i.e., break down the distinction between dynamical laws and initial conditions [6] such that it applies to the Universe as a whole.

Recently, we attempted another unification by unifying spacetime and matter as information via an informationally-complete quantum field theory, which describes elementary fermions, their gauge fields and spacetime (gravity) as a trinity [7, 8]. Therein, complete physical information of the trinity is encoded in dual entanglement—spacetime-matter entanglement and matter-matter (elementary fermions and their gauge

fields, together as matter) entanglement. The basic state-dynamics postulate [8] is that the Universe is self-created into a state $|e, \omega; A..., \psi...\rangle$ of all physical contents (spacetime and matter), from no spacetime and no matter, with the least action ($\hbar = c = 1$)

$$|e, \omega; A..., \psi...\rangle = e^{iS_{\text{GM}}(e, \omega; A..., \psi...)} |\emptyset\rangle, \\ \delta S_{\text{GM}}(e, \omega; A..., \psi...) |e, \omega; A..., \psi...\rangle = 0. \quad (1)$$

Here $|\emptyset\rangle \equiv |\emptyset_G\rangle \otimes |\emptyset_M\rangle$ is the common vacuum state of matter (the Minkowski vacuum $|\emptyset_M\rangle$) and geometry (the empty-geometry state $|\emptyset_G\rangle$ in LQG [2]); $A...$ ($\psi...$) represent all gauge (matter fermions) fields; gravity is described by the tetrad field e_μ^a and the spin connection ω_μ^{ab} , to be specified below. Note that the dynamical law and states always appear jointly in the postulate [Eq. (1)]. This is in sharp contrast to the tradition where the dynamical law [i.e., $\delta S_{\text{GM}}(e, \omega; A..., \psi...) = 0$] and states are given separately. Thus, besides the conceptual advantages as shown previously [8], the theory unifies the dynamical law and states.

The conceptual advantages of the informationally-complete quantum description motivate us to consider the ultimate unification of all known forces in this Letter. As is well-known, consistent superstring theory (or its updated version, the M -theory) exists only in $(9 + 1)$ - or $(10 + 1)$ -dimensional spacetime. Here we assume a $(9 + 1)$ -dimensional spacetime instead of the usual $(3 + 1)$ -dimensional one, but do not assume string and supersymmetry. We then consider the $(9 + 1)$ -dimensional Kaluza-Klein gravity [9] interacting with elementary matter fermions. The informational-completeness principle (ICP) requires that these fermions must appear in three families, each of which has 15 independent matter fermions. The ICP and compactifying 6 extra dimensions then lead to a trinity—the quantized $(3 + 1)$ -dimensional gravity, the three-family fermions of total number 45, and

their $SO(6)$ gauge fields.

Informationally complete unification of matter fermions.—Matter fermions in the SM are six quarks ($u, d; c, s; t, b$) and six leptons (electron e , electron neutrino ν_e ; muon μ , muon neutrino ν_μ ; tau τ , tau neutrino ν_τ). They can be precisely grouped into three “families” (or “generations”) as (ν_e, e, u, d) , (ν_μ, μ, c, s) , and (ν_τ, τ, t, b) . Together with the corresponding antiparticles, totally we have 45 matter fermions if each neutrino is merely left-handed. The three families have identical properties, except for distinct mass patterns. The origin of this amazing structure is a long-standing puzzle in the SM, which, together with the mass-generating Higgs mechanism, describes very successfully these fermions interacting via $SU(3) \times SU(2) \times U(1)$ gauge fields (the strong, weak, and electromagnetic forces). The particular SM group structure was discovered empirically; *there is no fundamental principle dicatating why we should choose this particular group, but not others* [10]. Some Grand Unification Theories (GUTs) extended the SM group into larger groups, such as $SU(5)$ [11] and $SO(10)$ [12, 13].

Here we assume a $(9+1)$ -dimensional spacetime (a curved manifold \mathcal{M}_{9+1}) with an $SO(9,1)$ symmetry, where the coordinates $x = (x^A) = (x^\mu, x^{\bar{\mu}})$ with “curved indices” $\mu = 0, 1, 2, 3$ and $\bar{\mu} = 4, 5, \dots, 9$. A Minkowski vector is denoted by $y = (y^I) = (y^a, y^{\bar{a}})$ with “flat indices” $a = 0, 1, 2, 3$ and $\bar{a} = 4, 5, \dots, 9$; the Minkowski metric η_{IJ} has signature $[-, +, \dots, +]$. Gravity in \mathcal{M}_{9+1} is then described by the tetrad field $\hat{e}_A^I(x)$ (with the inverse \hat{e}_I^A), which relates the $(9+1)$ -dimensional metric $\bar{g}_{AB}(x)$ via $\bar{g}_{AB}(x) = \hat{e}_A^I(x)\hat{e}_B^J(x)\eta_{IJ}$. As the $SO(9,1)$ group has 45 generators, gravity in \mathcal{M}_{9+1} has 45 independent field components and thus 90 independent internal states provided that the polarization degree of freedom (DoF) is taken in account.

Matter in \mathcal{M}_{9+1} is assumed to be an elementary fermion field ψ in the spinorial representation of $SO(9,1)$, which has $2^5 = 32$ dimensions. In terms of the Dirac matrices γ_a and γ_5 for $(3+1)$ dimensions and $\tilde{\gamma}_{\bar{a}}$ for six extra dimensions, one can construct 10 Γ -matrices [9]

$$\Gamma_a = \gamma_a \otimes I, \quad \Gamma_{\bar{a}} = \gamma_5 \otimes \tilde{\gamma}_{\bar{a}}, \quad (2)$$

which satisfy $\{\Gamma_I, \Gamma_J\} = \Gamma_I\Gamma_J + \Gamma_J\Gamma_I = 2\eta_{IJ}I$. These Γ -matrices then form the spinorial representation of $SO(9,1)$ as

$$[\Pi_{IJ}, \Pi_{KL}] = i(\eta_{IL}\Pi_{JK} + \eta_{JK}\Pi_{IL} - \eta_{IK}\Pi_{JL} - \eta_{JL}\Pi_{IK}), \quad (3)$$

with 45 generators $\Pi_{IJ} = \frac{i}{4}[\Gamma_I, \Gamma_J]$. The 32-dimensional representation implies that the matter fermions would have 32 independent internal states if no further constraint is required. However, the SM describes chiral fermions such that fermions of different chiralities transform differently under $SU(3) \times SU(2) \times U(1)$. In

particular, each fermion family has only 30 internal states (i.e., 15 independent matter fermions). Here we impose the same constraint as in the SM on the number of the internal states for the elementary fermion field ψ . As we show below, the constraint, together with the ICP, immediately explains why there are three and only three families of matter fermions in nature.

For this purpose, we need the total action of gravity and the elementary matter fermions in \mathcal{M}_{9+1} . We can use the beautiful language of differential forms to express the relevant geometry. For instance, $\hat{e}^I(x) = \hat{e}_A^I(x)dx^A$ represents 1-form. The infinitesimal rotation of \hat{e}^I is then a 2-form $d\hat{e}^I = -\hat{\omega}_J^I \wedge \hat{e}^J$ (Note that $d\hat{e}^I + \hat{\omega}_J^I \wedge \hat{e}^J \equiv \hat{T}^I$ is the torsion; here we consider therefore a torsion-free manifold), where an antisymmetric 1-form $\hat{\omega}^{IJ} = -\hat{\omega}^{JI}$ is the so-called spin connection. With the connection 1-form, a tensor 2-form $\hat{R}^{IJ} = d\hat{\omega}^{IJ} + \hat{\omega}_K^I \wedge \hat{\omega}^{KJ} = \hat{R}_{AB}^{IJ}dx^A dx^B$ can be defined and is known as the curvature. The scalar curvature reads $\hat{R} = \hat{R}_{AB}^{IJ}\hat{e}_I^A\hat{e}_J^B$. Now it is ready to write down the total action $S_{\text{GM}}^{(9+1)}(\hat{e}, \hat{\omega}; \hat{\psi}) = S_{\text{G}}^{(9+1)}(\hat{e}, \hat{\omega}) + S_{\text{G+M}}^{(9+1)}(\hat{e}, \hat{\omega}; \hat{\psi})$, where

$$S_{\text{G}}^{(9+1)} = \frac{1}{16\pi G_{10}} \int_{\mathcal{M}_{9+1}} dx^{10} \hat{e} \hat{R},$$

$$S_{\text{G+M}}^{(9+1)} = \frac{1}{2} \int_{\mathcal{M}_{9+1}} dx^{10} \hat{e} [\bar{\psi} \Gamma^I \hat{e}_I^A i D_A \psi + \text{H.C.}]. \quad (4)$$

Here G_{10} represents the Newton constant in \mathcal{M}_{9+1} , $\hat{e} = |\det \hat{e}_I^A|$; $\bar{\psi} = \psi^\dagger \Gamma^0$, the covariant derivative of Dirac’s spinors reads $D_A = \partial_A + i\hat{\omega}_A^{IJ}\Pi_{IJ}$.

After briefly summarizing known facts on gravity (in \mathcal{M}_{9+1}) interacting with fermions in the $SO(9,1)$ spinorial representation, let us consider the new input arising from our informational-completeness description. The state of spacetime (gravity) and matter reads [see Eq. (1)] $|\text{GM}\rangle = e^{iS_{\text{GM}}^{(9+1)}(\hat{e}, \hat{\omega}; \psi)} |\emptyset\rangle$. Generally speaking, the interaction between the Kaluza-Klein gravity and the matter fermions in $S_{\text{GM}}^{(9+1)}(\hat{e}, \hat{\omega}; \psi)$ generates gravity-matter entanglement. Unlike in current formulation of quantum mechanics, we cannot assume in the informational-completeness description any externally given measurement apparatus to measure a physical quantity, yielding classical records, as everything, even spacetime itself, is quantized here. Rather, we can only decompose the gravity-matter entangled state, which coherently stores complete information of the composite system, in a Schmidt form such that gravity and matter are mutually defined to acquire information [7, 8]. For our description to be informationally complete, the number of independent gravity field components and the number of independent matter fermions have to be the same, i.e., 45; otherwise, if we have more (less) gravity field components, then there will be redundant gravity field components (fermions) that do not entangle/interact with any fermions (gravity field

components). The redundant fields, either gravity or matter, are physically meaningless for acquiring information. Thus, *the ICP requires that there must be three and only three fermion families (duplicates), each of which has 15 independent matter fermions.* Hereafter, we then denote the matter fermion fields in Eq. (4) and $S_{\text{GM}}^{(9+1)}(\hat{e}, \hat{\omega}; \psi)$ by ψ_α with the family indices $\alpha = 1, 2, 3$.

Entanglement-driven symmetry breaking.—Now let us consider one more physical consequence of gravity-matter entanglement. Note that the family indices label a new internal space of fermions, or a new quantum number, which is physically different from the quantum number characterizing fermions of each family. Consequently, after gravity-matter entangling, the original internal spaces of the Kaluza-Klein gravity will be physically differentiated by the family quantum number and as such, the original $SO(9, 1)$ symmetry of the Kaluza-Klein gravity must be broken to a lower symmetry. This new mechanism of symmetry breaking can thus be called entanglement-driven symmetry breaking.

Mathematically, the maximal subgroup of $SO(9, 1)$ is $SO(3, 1) \times SO(6)$ which has the same rank (namely, 5) as $SO(9, 1)$. The most obvious way is thus to choose the lower symmetry to be $SO(3, 1) \times SO(6)$, resulting in the conventional $(3+1)$ -dimensional spacetime \mathcal{M}_{3+1} and 6-dimensional compactified space \mathcal{M}_6 (Other choices lead to inconsistencies this way or another by following the procedure given below). Then, according to the usual Kaluza-Klein mechanism, one can associate $SO(3, 1)$ (the Lorentz group) with the $(3+1)$ -dimensional gravity and $SO(6)$ with the gauge fields of matter fermions. Namely, we can expand $\bar{g}_{AB}(x)$ with the following ansatz [9, 14]

$$\bar{g}_{AB} = \begin{pmatrix} g_{\mu\nu}(x^\mu) - \tilde{g}_{\bar{\mu}\bar{\nu}}(x^{\bar{\mu}})W_{\bar{\mu}}^{\bar{\mu}}W_{\bar{\nu}}^{\bar{\nu}} & W_{\bar{\mu}}^{\bar{\mu}} \\ W_{\bar{\nu}}^{\bar{\nu}} & -\tilde{g}_{\bar{\mu}\bar{\nu}}(x^{\bar{\mu}}) \end{pmatrix} \quad (5)$$

with $W_{\bar{\mu}}^{\bar{\nu}} = \xi_{\bar{a}\bar{b}}^{\bar{\nu}}(x^{\bar{\mu}})\mathbf{Z}_{\bar{\mu}}^{\bar{a}\bar{b}}(x^\mu)$, where $\xi_{\bar{a}\bar{b}}^{\bar{\nu}}(x^{\bar{\mu}})$ is the Killing vectors appearing in the infinitesimal isometry $I + i\varepsilon^{\bar{a}\bar{b}}\Sigma_{\bar{a}\bar{b}} : x^{\bar{\nu}} \rightarrow x^{\bar{\nu}'} = x^{\bar{\nu}} + \varepsilon^{\bar{a}\bar{b}}(x^\mu)\xi_{\bar{a}\bar{b}}^{\bar{\nu}}(x^{\bar{\mu}})$; the infinitesimal parameters $\varepsilon^{\bar{a}\bar{b}}(x^\mu)$ are independent of $x^{\bar{\mu}}$. The ansatz (5), after integrating the extra dimensions in $S_{\text{GM}}^{(9+1)}(\hat{e}, \hat{\omega}; \psi)$, results in the $(3+1)$ -dimensional actions for gravity and for the $SO(6)$ gauge fields $\mathbf{Z}_{\bar{\mu}}^{\bar{a}\bar{b}}$ (with coupling constant g)

$$S_{\text{G}} = \frac{1}{16\pi G} \int_{\mathcal{M}_{3+1}} dx^4 e(R + \Lambda),$$

$$S_{\text{gauge}} = -\frac{1}{4} \int_{\mathcal{M}_{3+1}} dx^4 e \mathbf{F}_{\mu\nu}^{\bar{a}\bar{b}} \mathbf{F}_{\bar{a}\bar{b}}^{\mu\nu}, \quad (6)$$

where $e = |\det e_a^\mu| = \sqrt{-\det g_{\mu\nu}}$, Λ (G) is the usual cosmological (Newton) constant (for a discussion on the cosmological term, see Ref. [14]), and the $SO(6)$ field strengths

$$\mathbf{F}_{\mu\nu}^{\bar{a}\bar{b}} = \partial_\mu \mathbf{Z}_{\nu}^{\bar{a}\bar{b}} - \partial_\nu \mathbf{Z}_{\mu}^{\bar{a}\bar{b}} + g(\mathbf{Z}_{\mu}^{\bar{a}\bar{c}} \mathbf{Z}_{\nu}^{\bar{b}\bar{c}} - \mathbf{Z}_{\nu}^{\bar{a}\bar{c}} \mathbf{Z}_{\mu}^{\bar{b}\bar{c}}). \quad (7)$$

Thus, by treating \mathcal{M}_6 and \mathcal{M}_{3+1} on an equal footing, non-Abelian gauge fields naturally arise from a higher-dimensional gravity.

Finally, we notice that, as a result of symmetry breaking from $SO(9, 1)$ to $SO(3, 1) \times SO(6)$, the fermion field ψ_α for given family should be the spinorial representations of $SO(3, 1)$ and of $SO(6)$ *simultaneously*, which are 4- and 8-dimensional, respectively. The total dimensions of ψ_α are again 32 and reduced to 30 by imposing the chirality constraint. For detailed discussion on chirality in higher-dimensional spacetime, see Ref. [9].

Quantum compactification of extra dimensions.—As we argued previously [8], LQG plays an essential role for an informationally complete formulation of quantum field theory, in which we have to describe elementary matter fermions, their gauge fields, and gravity as a trinity. As gravity interacts (actually, entangles) universally with any form of matter, it is singled out within the formulation as a “programming system” [7, 8] of quantized matter fields—it entangles with elementary matter fermions and with their gauge fields *and* controls/programmes entanglement between elementary matter fermions and their gauge fields.

Usually, compactification of extra dimensions in the Kaluza-Klein and superstring theories is a complicated and unfinished issue. However, if we insist on the informationally complete trinary description as a robust theoretical structure, we could vastly simplify the problem of uncovering the reliable feature of the compactification without going into its detailed physics.

As we discussed above, there are three families of matter fermions. Quantum mechanically, the family information can be encoded by introducing three internal states $|F, \alpha\rangle$ attached on the fermion state space; $\{|F, \alpha\rangle\}$ forms a complete orthogonal basis. Any $|F, \alpha\rangle$ can be transformed into a new state by $|F, \alpha'\rangle = \exp(i\mathbf{R}_F \cdot \lambda^F)|F, \alpha\rangle$, where \mathbf{R} is a constant vector and λ operators defined in the family state space. Obviously, we could choose either $\lambda = (\lambda_1, \lambda_2, \lambda_3)$ being the $SO(3)$ generators in the spin-1 representation such that \mathbf{R} has three real components, or $\lambda = (\lambda_1, \lambda_2, \dots, \lambda_8)$ being the $SU(3)$ generators (the 3×3 Gell-Mann matrices in the matrix representation) such that \mathbf{R} has 8 real components. The ambiguity arises from the lack of details on compactification. Below we take, as an example, the $SO(3)$ case, which seems to be the most natural one.

Then according to the ICP, we have to introduce another quantum system interacting/entangling with the fermion family DoF such that the family information can be acquired. Such a quantum system can only be attributed to the compactified space in our theory because of the following reason. Note first that all physical DoFs related to the extra dimensions are quantized. If all these DoFs are completely entangled except that they only have three (the number is required

by the ICP to be the same as the family number) quantum states being free to entangle with the outside DoF, we can then simply take the outside DoF to be the family state space of matter fermions. In Ref. [8], based on quantum monogamy [15] of maximal entanglement we conjectured that the interior of a Schwarzschild black hole is maximally entangled so that external DoFs cannot entangle with and acquire information from the black-hole interior any more. In the “quantum compactification” mechanism proposed here, it seems that compactification results in a black-hole-like entity having only three “quantum hairs”, which form a simple three-state system.

Let us denote the three states of the compactified space by $|6D, \alpha\rangle$ and the spin-1 operator (like λ^F) defined in the state space $\{|6D, \alpha\rangle\}$ by λ^{6D} . Any $|6D, \alpha\rangle$ can be similarly transformed as $|6D, \alpha'\rangle = \exp(i\mathbf{R}_{6D} \cdot \lambda^{6D})|6D, \alpha\rangle$. The simplest form of the action (without the mass term) for the fermion sector then reads

$$S_{G+F}^{(\alpha)} = \frac{1}{2} \int_{\mathcal{M}_{3+1}} dx^4 e[\bar{\psi}_\alpha \gamma^a e_a^\mu i D_\mu \psi_\alpha + \text{H.C.}], \quad (8)$$

such that the total evolution operator is

$$U_{GM} = \sum_\alpha |6D, \alpha\rangle \langle 6D, \alpha| e^{iS_{\text{ung}}^{6D}} \otimes e^{i[S_G + S_{\text{gauge}} + S_{G+F}^{(\alpha)}]} \quad (9)$$

to entail interaction (e.g., an isotropic spin-spin coupling $\propto \lambda^F \cdot \lambda^{6D}$) or entanglement between the fermion family state space and the compactified space. Here $D_\mu = \partial_\mu + i\omega_\mu^{ab}\Pi_{ab} + ig\mathbf{Z}_\mu^{\bar{a}\bar{b}}\Pi_{\bar{a}\bar{b}}$ and the repeated family indices α are not summed automatically in Eq. (8); $S_{\text{ung}}^{6D} = \mathbf{R}_{6D} \cdot \lambda^{6D}$ to account for the rotations of states for the compactified space. Obviously, $SO(3)$ for \mathcal{M}_6 is not gauged and denoted by $SO_{\text{ungauge}}(3)$. Note also that, as $\{|6D, \alpha\rangle\}$ is a “programming basis” [7, 8], we can and should have a relation $[U_{GM}, S_{\text{ung}}^{6D}] = 0$ due to the dynamics-state unification.

The potential impact of the proposed quantum compactification mechanism on the cosmological term is certainly an interesting problem. Seen from the Kaluza-Klein approach, the cosmological term gathers the effects of compactified space on gravity in \mathcal{M}_{3+1} [14], i.e., the “leaked” interaction or information between \mathcal{M}_{3+1} and \mathcal{M}_6 in certain sense. Nevertheless, \mathcal{M}_6 is supposed here to compactify into a black-hole-like entity with only three quantum states leaked outside and coupled with the fermion sector; its leaked information into the gravitational DoFs in \mathcal{M}_{3+1} , if any, should be extremely small from an information point of view. Thus, our quantum compactification mechanism seems to imply a small Λ , although the analysis is highly speculative.

Action for all forces and dynamics.—To sum up the above results, the total action in \mathcal{M}_{3+1} is defined by

$$U_{GM} \equiv \exp[iS_{\text{GGUT}}], \quad (10)$$

where GGUT stands for “gravitational GUT” (GUT with gravity). Such a GGUT is informationally complete, as argued, and seems to be impossible to reach if we ignore gravity from the outset. Note that $S_{\text{GGUT}} \neq S_G + S_{\text{ung}}^{6D} + S_{\text{gauge}} + S_{G+F}$. Below we consider the dynamics of the physical Universe described by $S_{\text{GGUT}}^{(3+1)}$.

It is well-known that the Lorentz algebra $SO(3,1)$ is locally isomorphic to $SU(2) \times SU(2)$. Here one $SU(2)$ generates the rotations and another the boosts. In LQG, gravity in \mathcal{M}_{3+1} possesses only one $SU(2)$ gauge structure [denoted by $SU_G(2)$] related to the rotations, while the boost DoFs are not dynamical [16]. After the $3+1$ spacetime decomposition and taking the time gauge, one arrives at the Hamiltonian formalism [2, 4]. The dynamical variables of the $SU(2)$ gravity, in terms of e_a^μ and ω_μ^{ab} , are the connection field \hat{A}_m^r [defined on \mathcal{M}_3 ; m : spatial indices and r : $SU(2)$ -valued], whose conjugate variable is the “gravitational electric field” $\hat{E}_n^s(\tau)$. The canonical dynamical variables for $\mathbf{Z}_\mu^{\bar{a}\bar{b}}$ and ψ_α , whose explicit forms are not important in subsequent discussions, can also be obtained within LQG. A remarkable result of LQG is to identify the state space of quantized gravity, spanned by a complete orthogonal basis $\{|\Gamma, \{j_l\}, \{i_n\}\rangle\}$ consisted of the spin-network states with respect to an abstract graph Γ (with nodes n and oriented links l) in three-dimensional region \mathcal{R} with boundary $\partial\mathcal{R}$. Here j_l is an irreducible j representation of $SU(2)$ for each link l and i_n the $SU(2)$ intertwiner for each node n .

The informationally complete trinary description allows us to adopt either a “global view” or a “local view”. The global view is reflected by the fact that all physical predictions about the whole Universe are encoded in gravity-matter entanglement $|\mathcal{A}, (\psi_\alpha, \alpha, \mathbf{Z})\rangle = e^{iS_{\text{GGUT}}}|\emptyset\rangle \otimes |6D, \alpha_0\rangle$ for given “initial state” $|6D, \alpha_0\rangle$ of \mathcal{M}_6 . Thanks to the spin-network basis,

$$|\mathcal{A}, (\psi_\alpha, \alpha, \mathbf{Z})\rangle = \sum_{\substack{l \in \Gamma \cap \partial\mathcal{R} \\ n \in \Gamma \cap \mathcal{R}}} S_\Gamma(l, n) |\mathcal{A}, \Gamma, j_l, i_n, t\rangle \otimes |(\psi_\alpha, \mathbf{Z}); 6D; \Gamma, l, n; t\rangle. \quad (11)$$

Here t denotes time; $|(\psi_\alpha, \mathbf{Z}); 6D; \Gamma, l, n; t\rangle = \sum_\alpha M_\alpha |(\psi_\alpha, \alpha, \mathbf{Z}); \Gamma, l, n; t\rangle |6D, \alpha\rangle$ in the Schmidt form for $\{|\mathbf{F}, \alpha\rangle\}$ and $\{|6D, \alpha\rangle\}$, and M_α (related to $|6D, \alpha_0\rangle$ and \mathbf{R}_{6D}) and S_Γ are the Schmidt coefficients. S_Γ must be time-independent as $|\mathcal{A}, (\psi_\alpha, \alpha, \mathbf{Z})\rangle$ is annihilated by the total Hamiltonian, known as the Hamiltonian constraint. As a spin-network state $|\mathcal{A}, \Gamma, j_l, i_n, t\rangle$ defines spacetime and thus, is spacetime [2], we can include t (together with \mathcal{A}) explicitly in $|\mathcal{A}, \Gamma, j_l, i_n, t\rangle$. $|(\psi_\alpha, \mathbf{Z}); 6D; \Gamma, l, n; t\rangle$, programmed by a given spin-network state, encodes entanglement between (i.e., all physical predictions about) matter fermions and their gauge fields. Such a particular entanglement structure of the Universe is called dual entanglement [7, 8]. Following Ref. [8], the dynamics of the Universe

can be cast into a dual form without the notorious “problem of time” [2, 4] in quantum gravity, thus recovering a description of the local view.

Note that all states for gravity, matter fermions, and gauge fields, once Schmidt-decomposed in the dual form, are physical predictions of the theory and thus must be annihilated automatically by any constraints appearing in the theory. This fact embodies again that our formalism unifies the dynamical law and states.

Possible routes to the Standard Model.—So far, our GGUT theory predicts, in certain sense, some basic facts that are used in the SM without any fundamental explanations. These include the dimensions of spacetime, the three-family pattern, and the number of elementary matter fermions. However, if the theory does be a GGUT, it must predict the SM in certain manner.

At present, we can only envision some possible routes to the SM. First of all, the $SO(6)$ symmetry of the unified gauge fields in our theory should be further broken to explain the SM group $SU(3) \times SU(2) \times U(1)$. At first sight it seems that the $SO(6)$ symmetry is too small to achieve this. However, for the fermion sector the effective symmetry of dynamical significance is actually $SO(6) \times SO_{\text{ungauge}}(3)$, though $SO(3)$ is ungauged. Perhaps there could be certain mechanism (e.g., family mixing) to escape the smallness of the $SO(6)$ symmetry by “borrowing” from the ungauging symmetry. Interestingly, the overall symmetry of dynamical significance is $SO(6) \times SU_G(2) \times SO_{\text{ungauge}}(3)$, which is isomorphic to $SO(6) \times SO(3, 1)$.

A more radical route might be to regard the currently-known fermions as composite particles. Along this line, the elementary matter fermions interact via the unified gauge fields of the $SO(6)$ symmetry. When they form composite particles, the composite particles should have lower symmetries. Taking the Harari-Shupe rishon model [17, 18], in which no rishon dynamics was suggested, as an example, we could describe three-family rishons by our dynamical theory; the masses of the observed fermions, $SU(2)$ gauge bosons, and Higgs bosons might stem from the binding energies of rishons.

Conclusions and discussions.—To summarize, insisting on the informational-completeness trinary description of nature, we have described very briefly, with details to be given elsewhere, a unified theory for all forces and matter. Seen from our discussion, the following two facts are strictly related or even mutually explained, namely, (1) matter fermions have three families, each having 15 independent matter fermions, and (2) spacetime is (9+1)-dimensional and displays entanglement-driven symmetry breaking from $SO(9, 1)$ down to $SO(3, 1) \times SO(6)$. The latter fact in turn explains why the observed spacetime is \mathcal{M}_{3+1} and the gauge group for matter fermions is $SO(6)$. The informational-completeness trinary description of our theory naturally arises, thus demonstrating that the overall picture is consistent with our previous insistence

on the informational completeness. Indeed, the ICP works as *the* fundamental principle restricting not only the required gauge group, but more, such as the dimensions of spacetime and the number of elementary matter fermions. Due to the discreteness of spacetime acting as a natural regulator [19] and severe limitation of information by the informationally complete trinary description, our theory should be free of singularities. Assuming a pure Kaluza-Klein mechanism and the ICP, the theory seems to be unique.

Surely, there are a lot of open questions. First of all, it reminds to be seen how to reconcile our theory with the SM, by further entanglement-driven symmetry breaking. In this regard, the mass-generation mechanism is a particularly interesting issue. What is the detailed physics of quantum compactification? Is it possible to introduce supersymmetry/superstring in the informationally complete field theory? As supersymmetry predicts too many new particles that are hard to suit the informational completeness, the answer to the question seems to be gloomy. If this is indeed the case, the informational completeness could be a strong reason to exclude supersymmetry. Another interesting problem is to integrate the Randall-Sundrum mechanism [20] within our theory by considering warped extra dimensions.

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